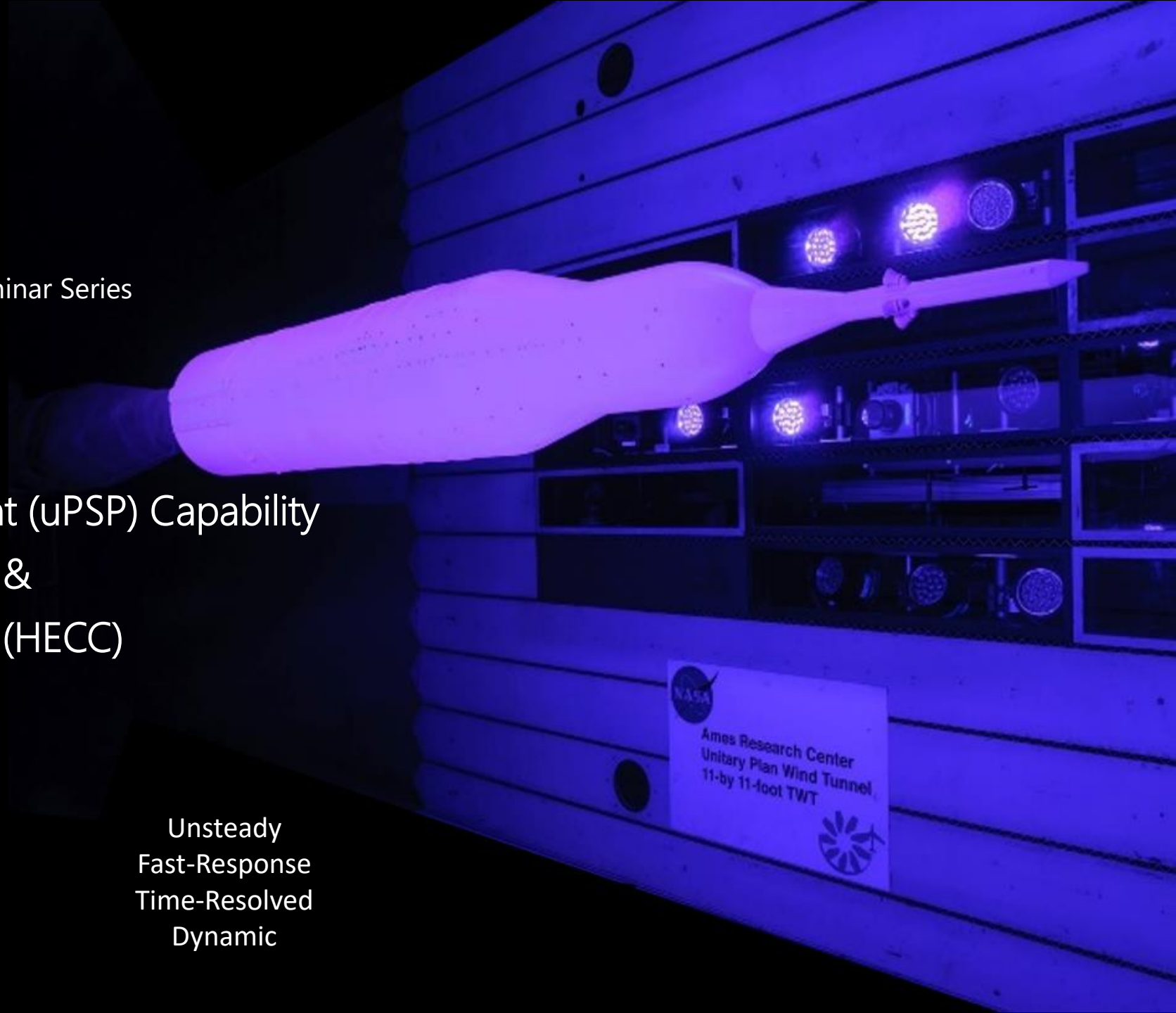
NASA Ames Research Center

Advanced Modeling & Simulation (AMS) Seminar Series

Development of NASA's Unsteady* Pressure-Sensitive Paint (uPSP) Capability with Space Launch System (SLS) & High-End Computing Capability (HECC)



Nettie Roozeboom

NASA Ames Research Center

April 14, 2022

Unsteady
Fast-Response
Time-Resolved
Dynamic

AMS Series Highlighting Contributions Towards NASA SLS & Orion

- **March 17**
  - Francois Cadieus:
  - Predicting Orion Launch Abort Acoustics
- **March 24**
  - Jordan Angel
  - Towards Multiphase Simulations of Launch Environments for Acoustic Predictions.
- **March 31**
  - Derek Dalle & Jamie Meeroff
  - Advances in Launch Vehicle Ascent and Booster Separation CFD
- **April 7**
  - Ryan McDaniel
  - Orion Aerosciences
- **April 14**
  - Nettie Roozeboom
  - Development of NASA's Unsteady Pressure-Sensitive Paint (uPSP) Capability with Space Launch System (SLS) High-End Computing Capability (HECC)

Thank you, Dr. Cetin Kiris, for the organization and promotion of the AMS Seminar Series.

The work of many hands

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Craig Streett
Jeremy Pinier
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Glenn Research Center
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Contract Companies
Jacobs Technology
Metis Flight Research Associates
Aerospace Computing Inc
Science & Technology Corp.
ASRC Federal

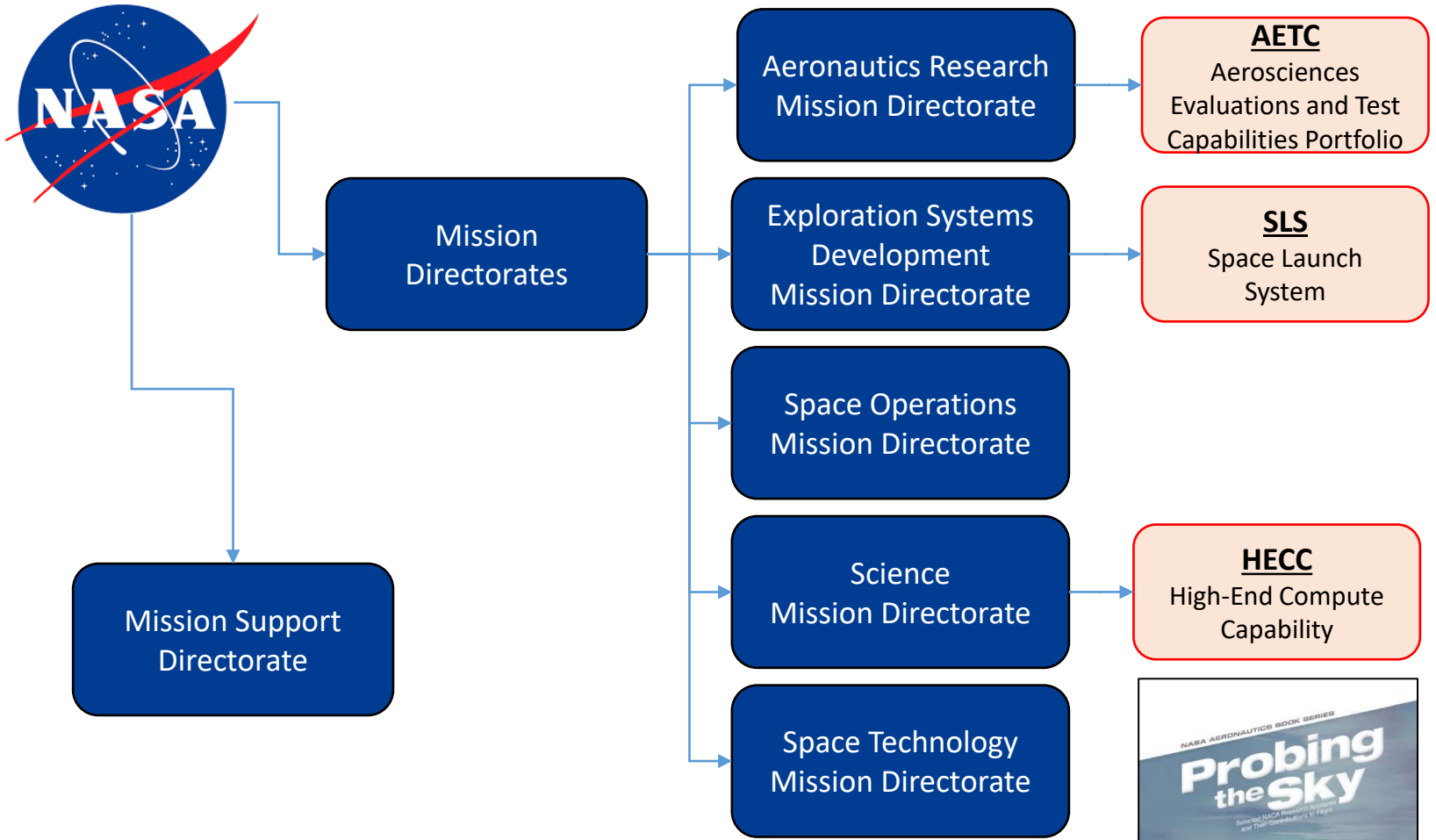
NASA Programs
AETC
NESC
SLS
HECC

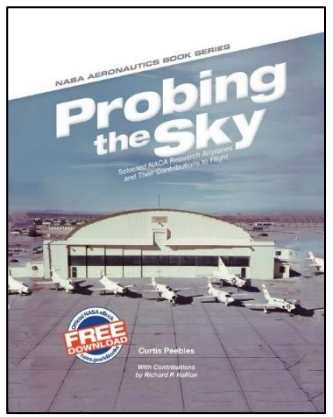
"All in all, for someone who was immersed in, fascinated by, and dedicated to flight. I was disappointed by the wrinkle in history that had brought me along one generation late. I had missed all the great times and adventures in flight.
~ Neil Armstrong (1947)

Goals of the Seminar

- Introduce experimental facilities and experimental testing.
- Introduce Pressure-Sensitive Paint (PSP) technology
- Give motivations for why the development of unsteady PSP (uPSP) is valuable
- Highlight the development of uPSP and the collaboration with NASA's SLS program.
- To solve challenging problems in Aerosciences,
  the experimental and computational facilities and communities must be closely connected.
  - People + Facilities + Tools
  - Facilitate advancements in model-based engineering, data-driven modeling

Aerosciences Evaluations and Test Capabilities Portfolio





https://www.nasa.gov/connect/ebooks/probing_the_sky_detail.html

- Responsible for NASA's ground testing capabilities
- AETC Goals:
  - Provide the **tools** to deliver the technology innovations and breakthroughs necessary **to address** the increasingly **complex** research and development **challenges**
  - AETC's integrated approach will consider the complementary high-end computing capabilities necessary for advanced analyses in conjunction with ground experimental capabilities.

NACA's X-plane research and capabilities is what built NASA.

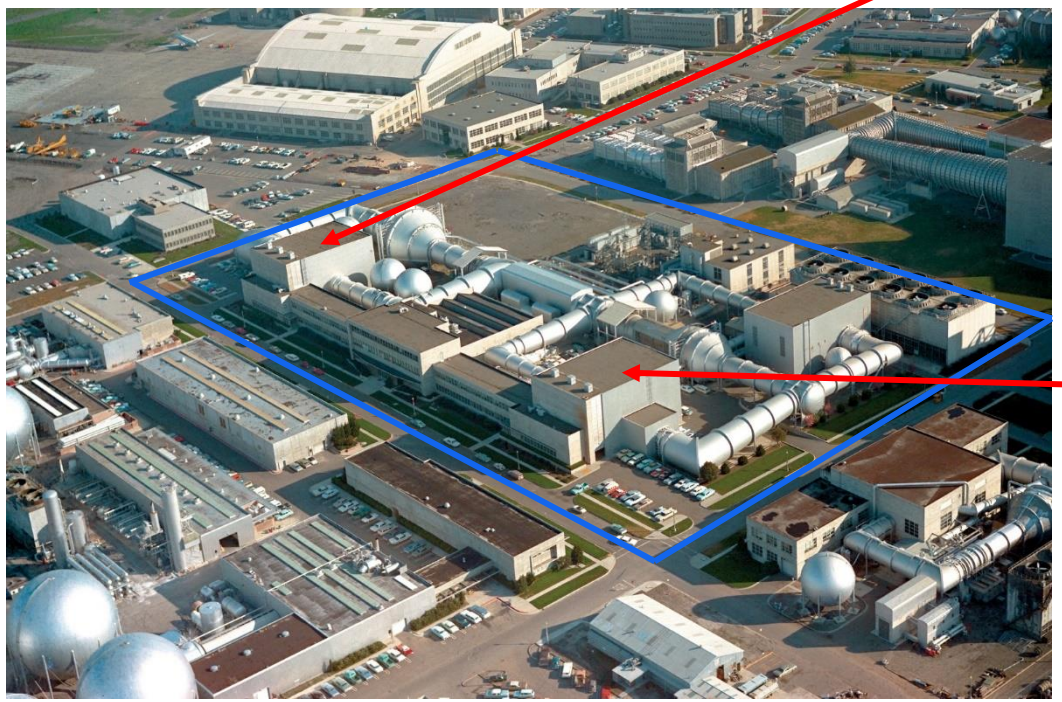
The culture, people, processes, technology, and facilities that allowed NASA to successfully lead the space programs.

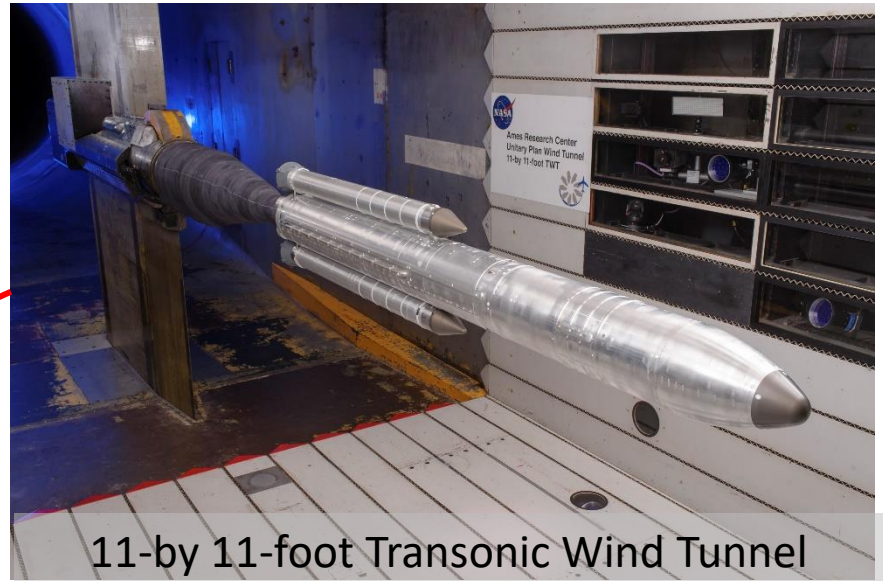
Aerosciences Evaluations and Test Capabilities Portfolio

Aeronautics Research Mission Directorate

AETC
Aerosciences Evaluations and Test Capabilities Portfolio

- Ames Research Center
  - Unitary Plan Wind Tunnel
- Glenn Research Center
- Langley Research Center





11-by 11-foot Transonic Wind Tunnel

9-by 7-foot Supersonic Wind Tunnel

NASA - Agency Goals

NASA ARMD

- **Strategic Thrust 3: Ultra-Efficient Commercial Vehicles**
  - Large leaps in **aircraft efficiency**
  - Reduce noise and harmful emissions
  - Develop critical **technologies**

- **Strategic Thrust 4: Transition to Low-Carbon Propulsion**
  - High efficiency electric propulsion
  - Electrified Aircraft Propulsion is an enabler for enhancing efficiency of transport-class aircraft, improving economics for small, short-range aircraft.
  - Work with aviation market communities

NASA HEOMD

- **Project Artemis**
  - 'Move forward in **design**, development, exploration'
  - 'Envision a strong **commercial partnership** to help increase innovation and reduce cost to American tax payer' – Administrator Bridenstine, May 13, 2019
- **Commercial Lunar Payload Services (CPLS)**
  - NASA is working with nine American companies on delivery services to lunar surface.
  - Companies bid on delivering science & technology payloads for NASA, **including launch from Earth** and landing on moon.
  - NASA will look at technical, price, and schedule.
  - Several of these companies have expressed interest in uPSP.

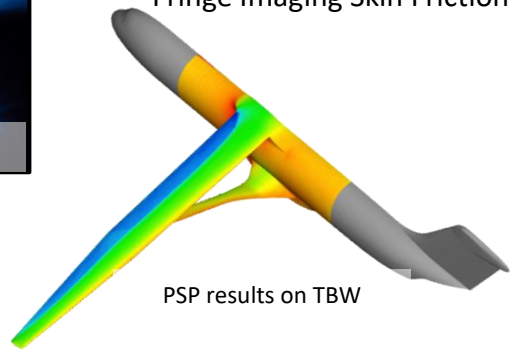
Ground Tests & Their Measurements

Aerodynamic Forces
Surface Pressure over some Area

Quantify **Steady**, Time-Averaged Forces

NASA/Boeing TBW model coated with PSP.

- Balance
- Pressure taps
  - can be expensive
  - limited in number
  - spatial limitation
- Optical Technique
  - Pressure-Sensitive Paint (PSP)
  - Shadowgraph
  - Infrared Thermography (IR)
  - Model Deformation Measurement
  - Fringe Imaging Skin Friction (FISF)



PSP results on TBW

Ground Test Toolbox
- Balances
- Strain Gages
- Thermocouples
- Pressure Transducers
- Optical Techniques

CFD Simulation Toolbox

Flight Test Toolbox

Quantify **Unsteady**, Time-Resolved Forces

The next major challenge for aero- and fluid dynamics is the understanding of unsteady flows. It is the performance-limiting factor for many flight vehicles and dictates the structural requirements for launch vehicles and their payloads.

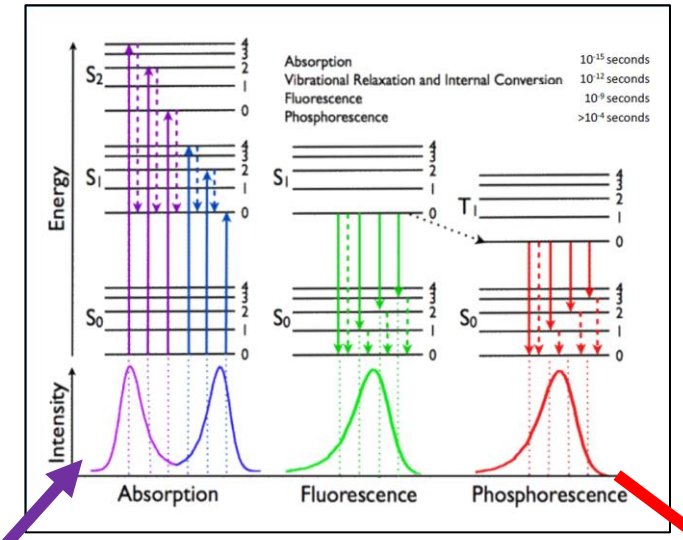
\- David Schuster, NASA Aerosciences Technical Fellow

- **To understand unsteady aero-physics, must measure unsteady surface pressure.**
- The ability to ***measure*** and ***compute*** these flows remains a challenge.
- Improving the state of the art, will reduce margins

Pressure-Sensitive Paint (PSP) Background

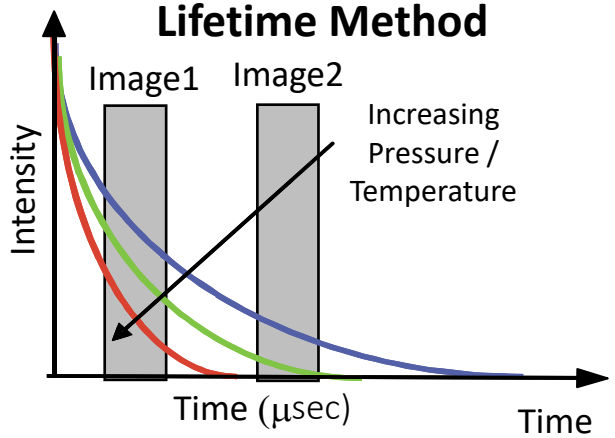
- PSP research started late 1980's, University of Washington & NASA
- PSP exploits oxygen sensitivity of luminescent molecules.

Jablonski Diagram



- Luminescent molecule is reacting with oxygen molecules in the air.
- The oxygen molecules will 'quench' the luminescent molecule

Luminescent molecule is excited by high energy photon (400-nm)



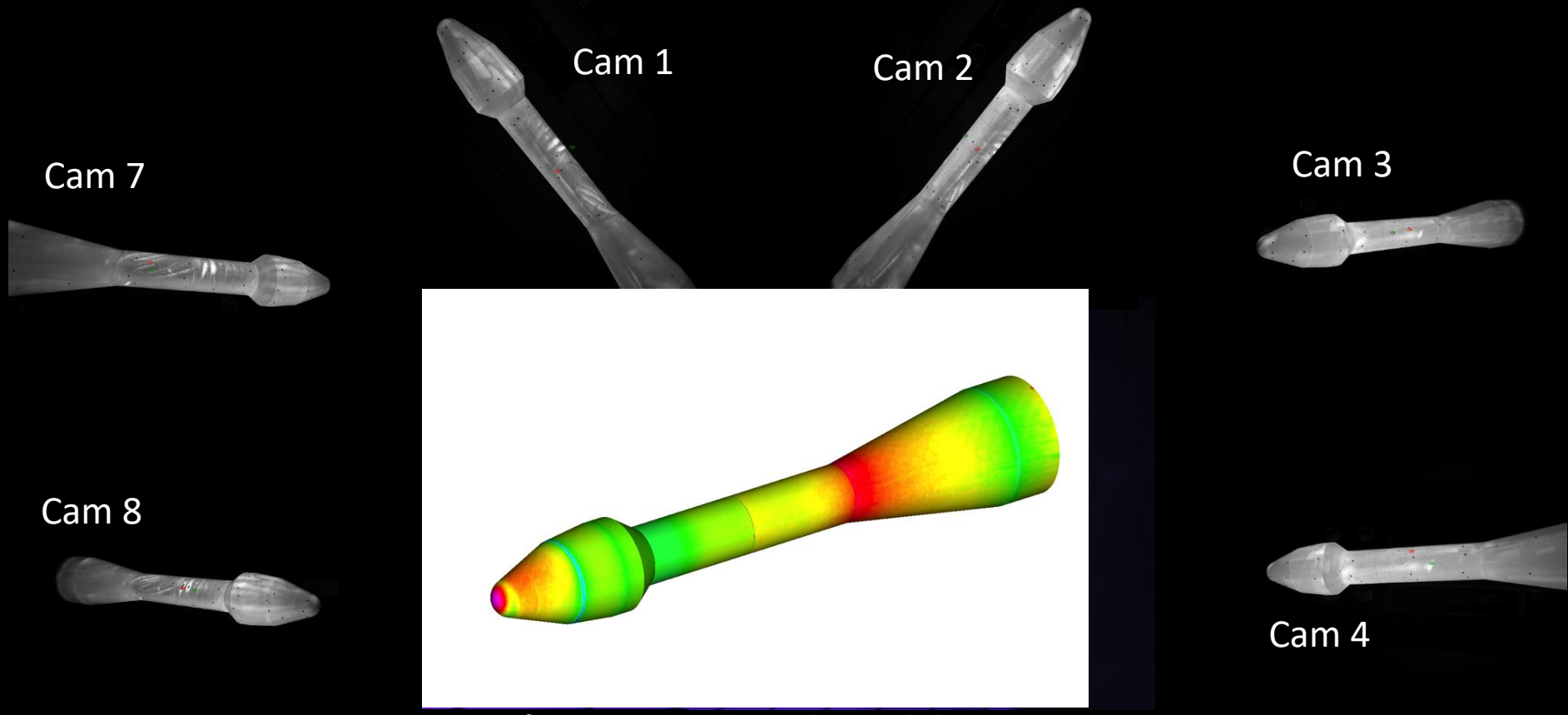
AIAA2017-1055

followed by emission of a lower energy photon (650-nm)

Higher Oxygen Concentration = Higher Pressure = Lower Emitted Intensity

nasa.gov article – 'Power of Pink'

PSP Background



Images from 8 cameras located around the test section are combined to form a 3D map of the pressure distribution.

Past Applications of Lifetime PSP

NASA X-planes

NASA ERA

NASA HEOMD

NASA NESC

Commercial Crew

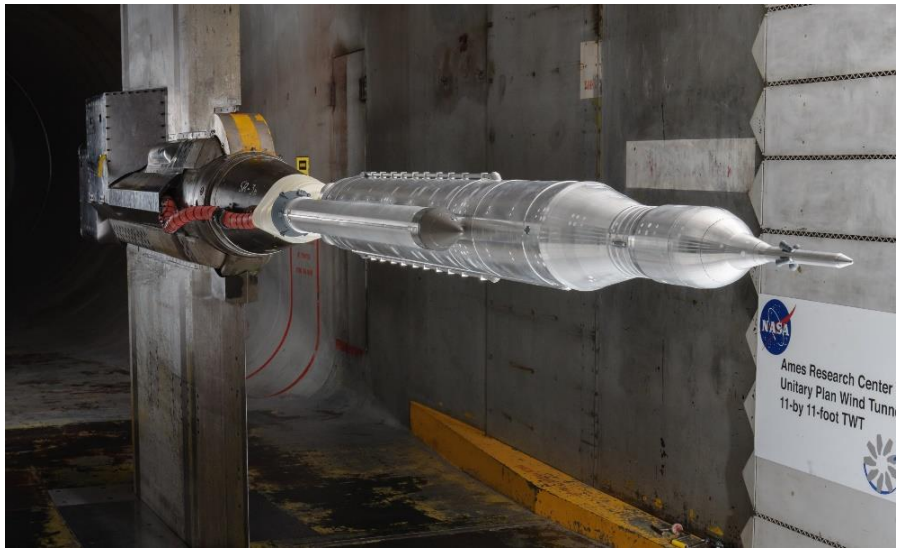
Challenge

NASA and its Stakeholders are developing increasingly advanced aerospace vehicles

NASA GRC 8x6 SWT - BLI

NASA Army 7x10 Low Speed WT - Octocopter

NASA NFAC 40 x 80 – Active Flow Control



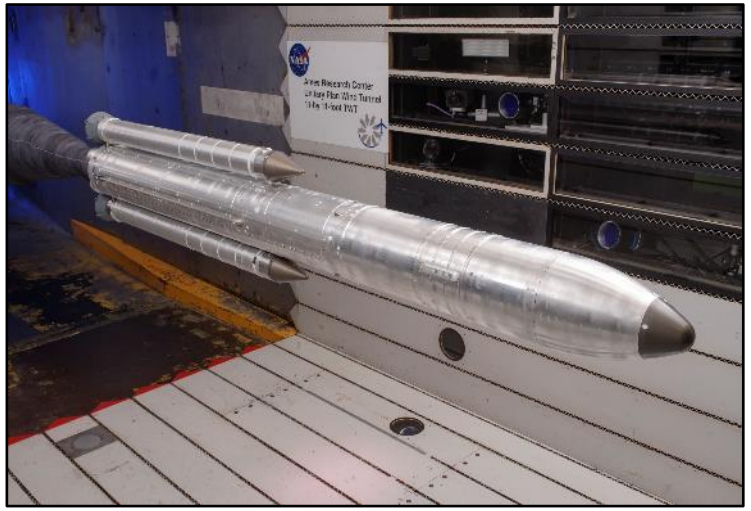
NASA ARC 11x11 TWT – SLS Crew

Current method

July 2013

- July 2013: t11-0265
  - Launch vehicle buffet forcing functions (BFF) estimated from sparse, unsteady pressure measurements (Kulites)
  - Rocket was too heavy
  - Formed a special task team to investigate why
  - Details of the pressure integration scheme are critical to getting the right answer
- Dec 2013: t11-0273
  - SLS spent significant effort refining BFF estimates
  - Improved processing to refine estimates and added instrumentation for a repeat test
  - Effort highlighted need for high spatial resolution pressure data to evaluate BFF estimation techniques
- Dec 2017: t11-0344
  - Added more instrumentation, repeated test

Dec 2013



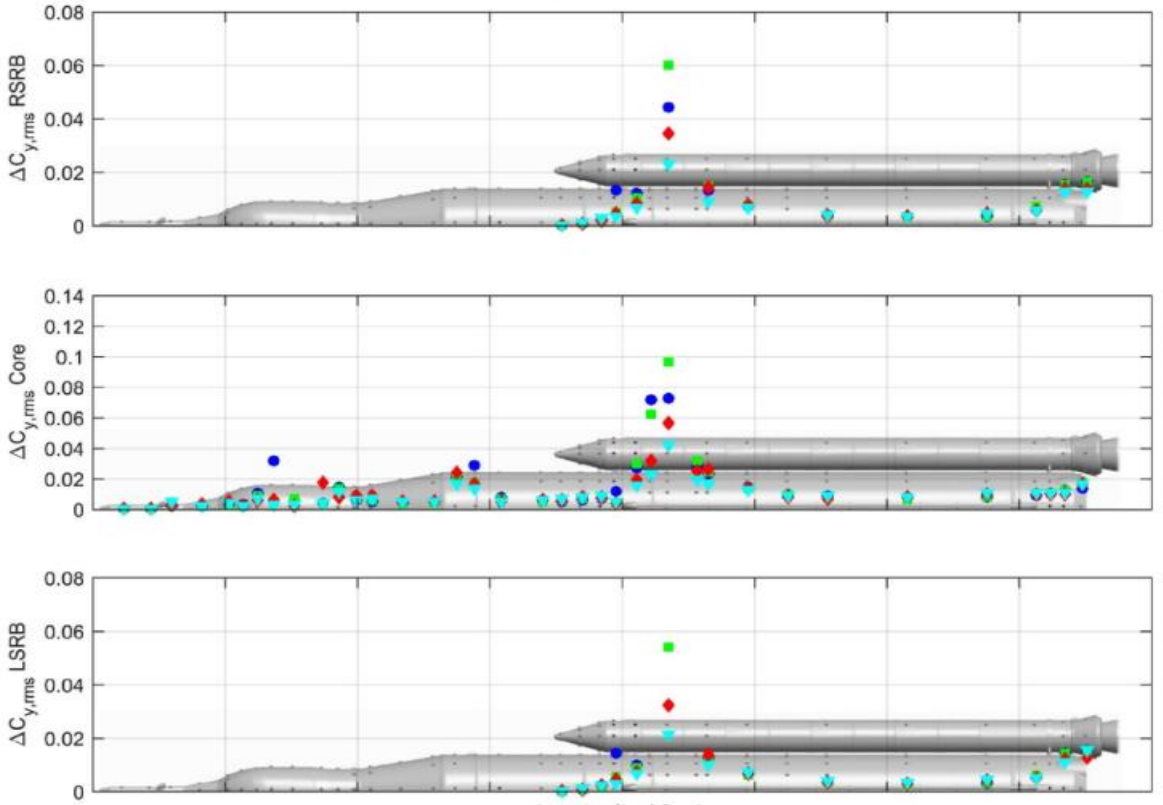
Dec 2017

Where's the Gap

- **Simulation Data from CFD**
  - Surface pressure measurements
  - High spatial resolution
  - Limited high temporal resolution

AIAA2015-0778 - Rogers, Dalle, Chan

- **Experimental Data from Transducers**
  - Surface pressure measurements
  - Limited spatial resolution
  - High temporal resolution



BFF Estimates from Experimental Data

AIAA2016-0544 - Piatak, Sek8ula, Rauch

Mission: Transform the Ability to Assess Unsteady Flow Phenomena

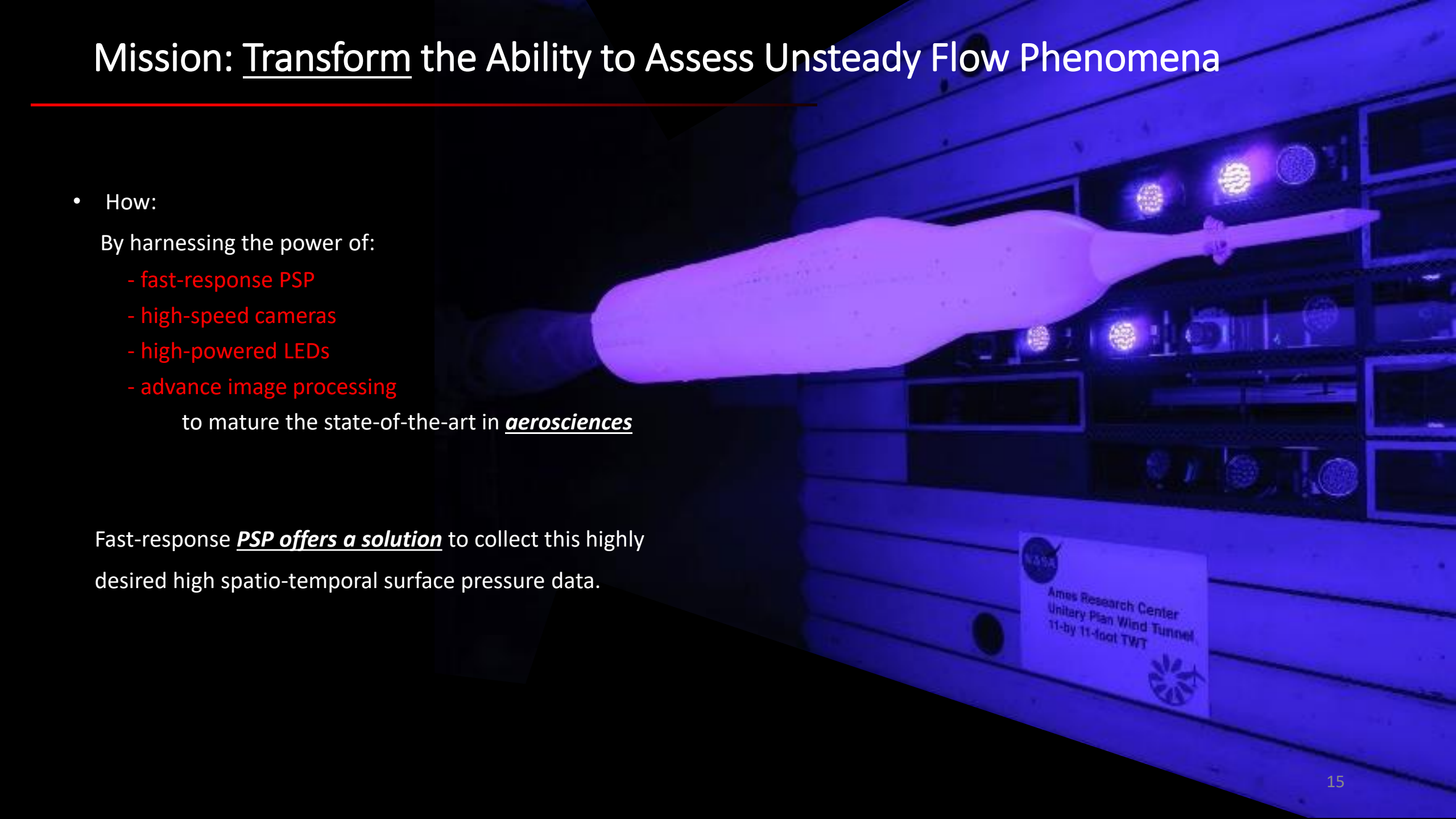
- How:

  By harnessing the power of:

  - fast-response PSP
  - high-speed cameras
  - high-powered LEDs
  - advance image processing

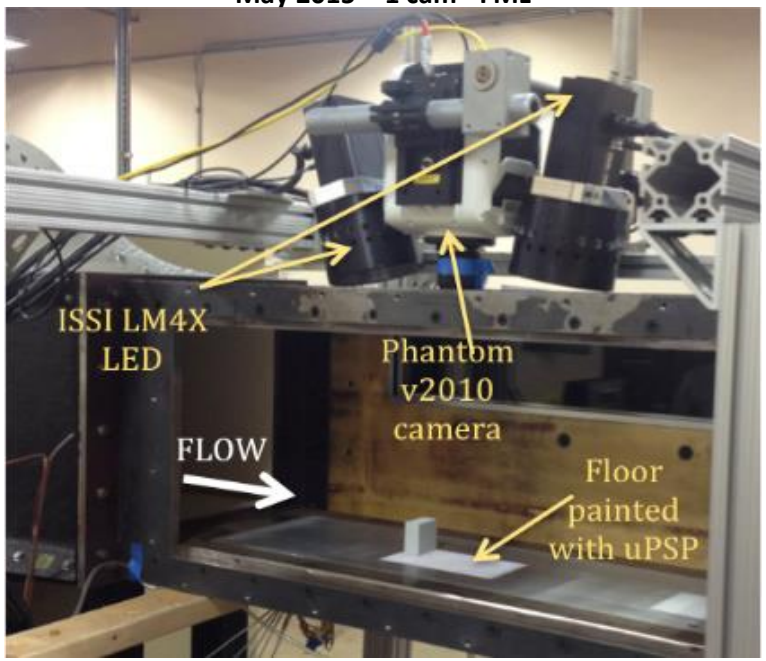
  to mature the state-of-the-art in ***aerosciences***

Fast-response ***PSP offers a solution*** to collect this highly desired high spatio-temporal surface pressure data.

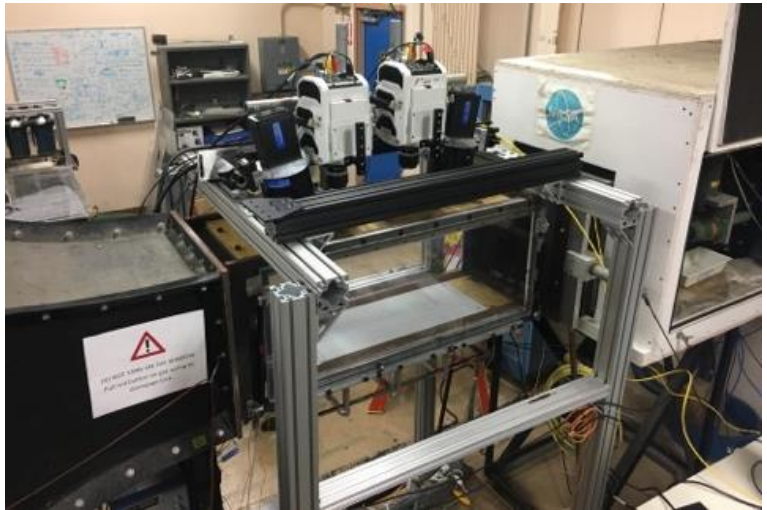


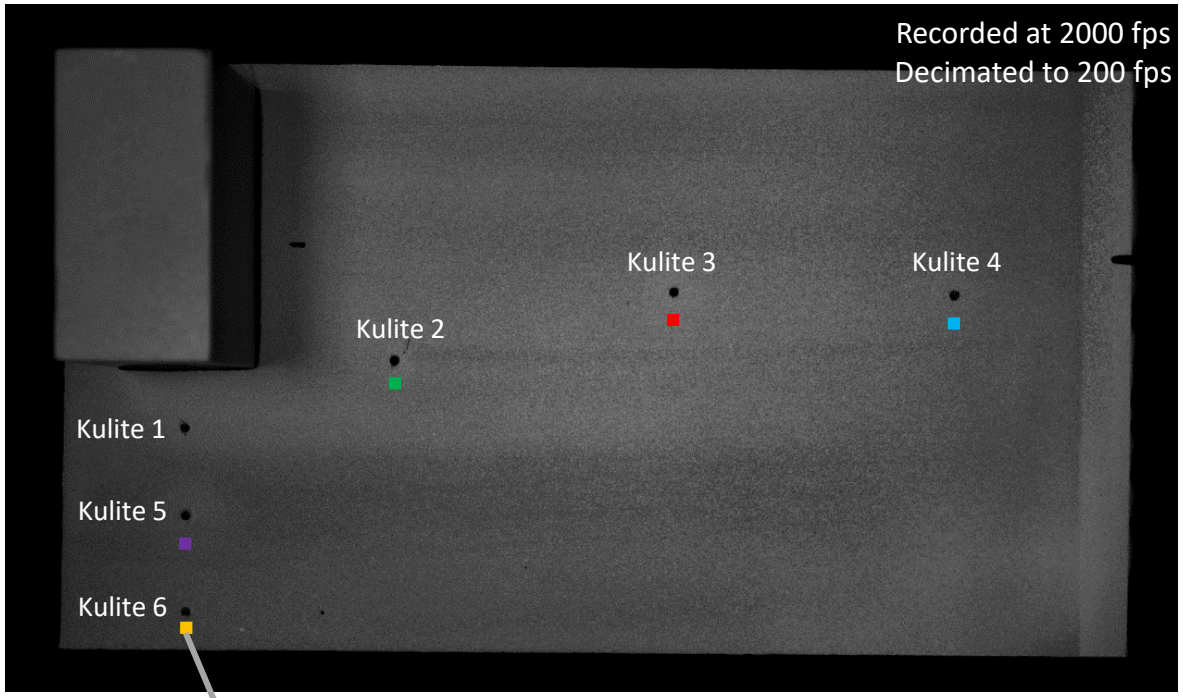
Timeline of uPSP development

May 2015 - 1 cam - FML

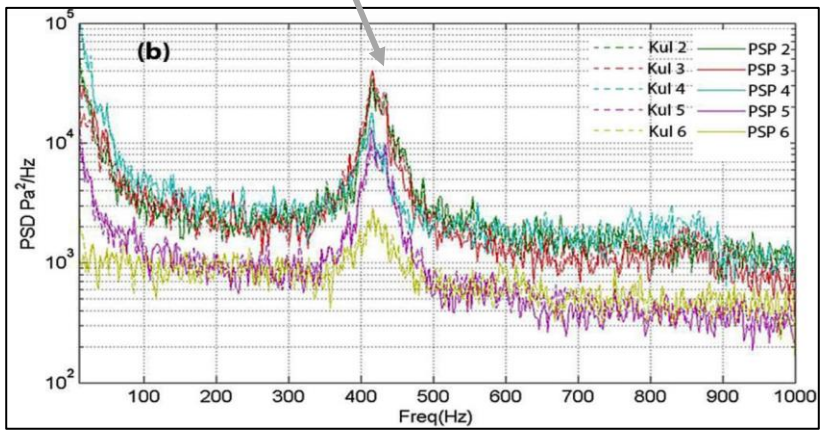


Mar 2017 - 2 cam - FML





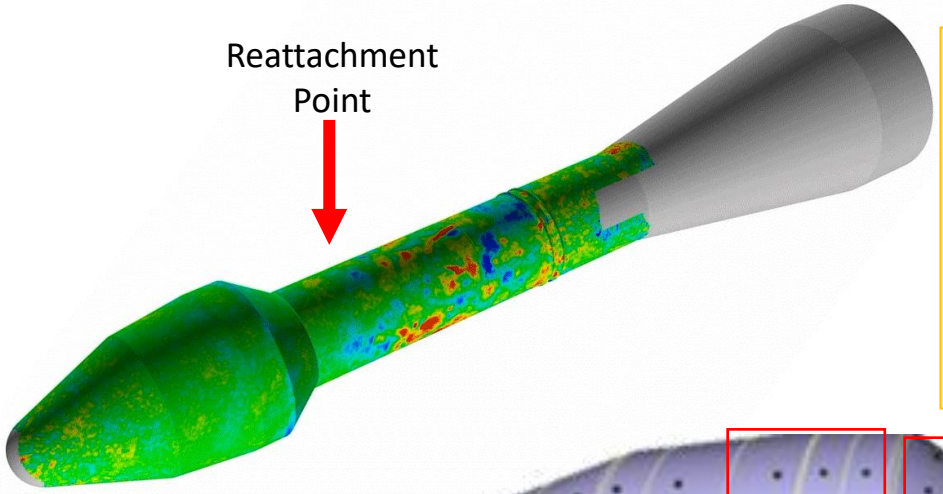
AIAA2016-2017



- Unable to distinguish Kulite data from PSP data.
- High confidence to continue development

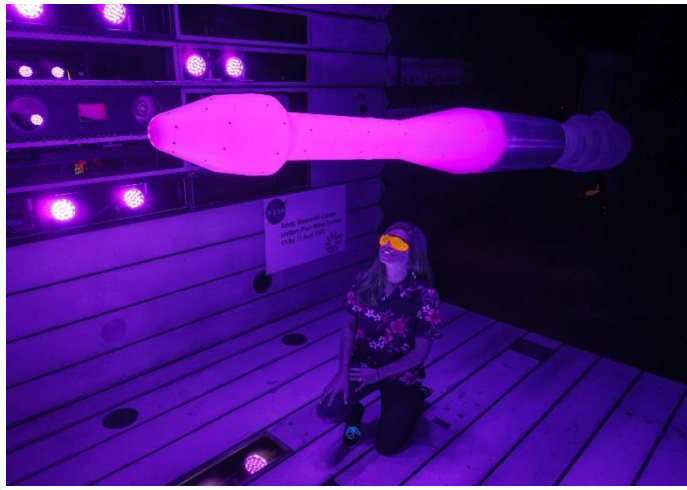
AIAA2016-3007

Launch Vehicle Buffet Test



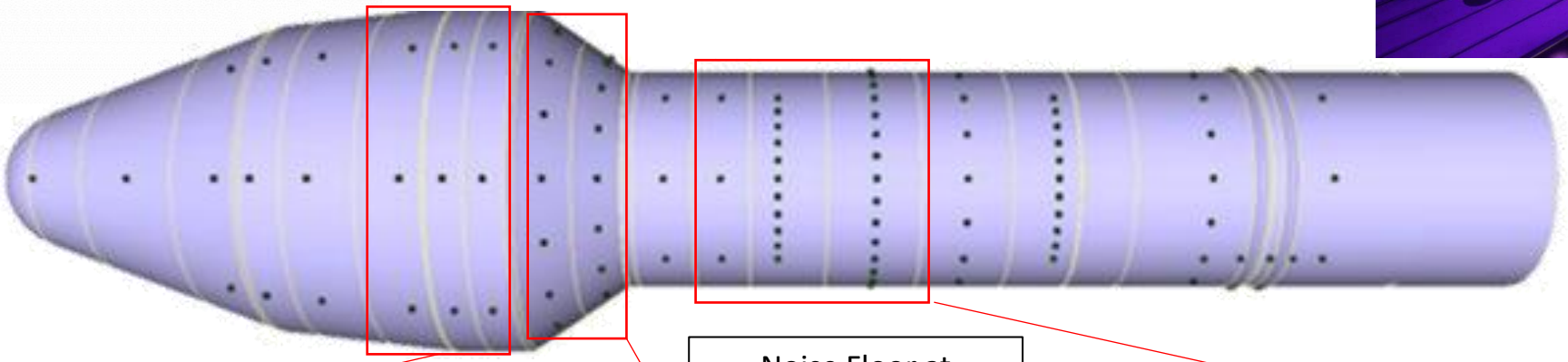
From the NESC Report (14-00962)

- **Current practice usually results in overly-conservative buffet forcing functions.**
- **Modification to current technique can improve the accuracy of buffet estimates.**

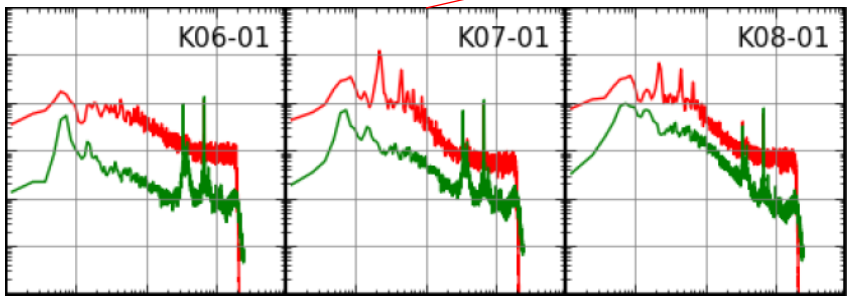


Nov 2015

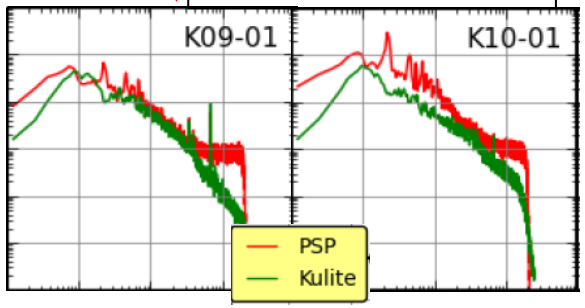
AIAA2017-1402
AIAA2017-1403
AIAA2017-1404
AIAA2017-1405
AIAA2017-1406
NASA/TM-2016-219352



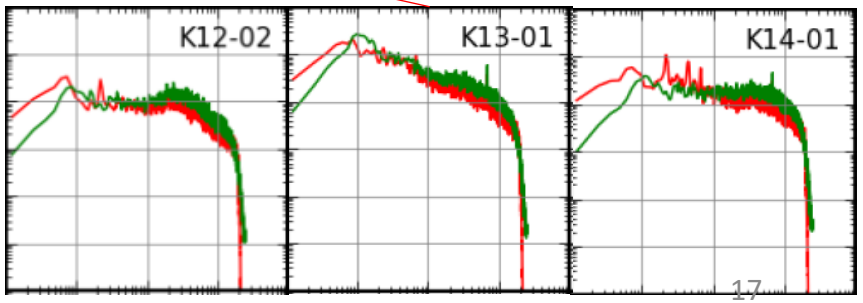
Low SNR



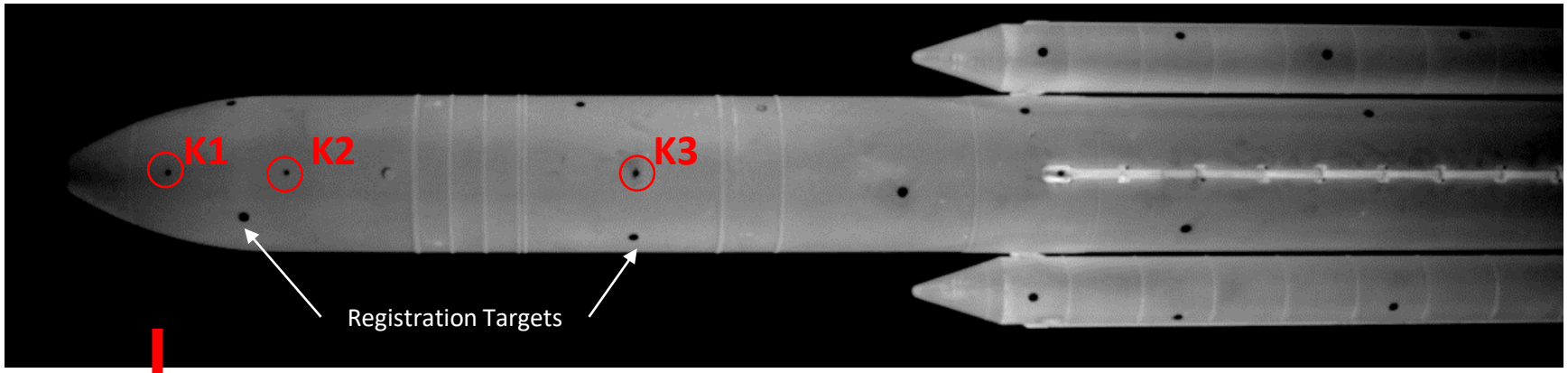
Noise Floor at
High Frequency



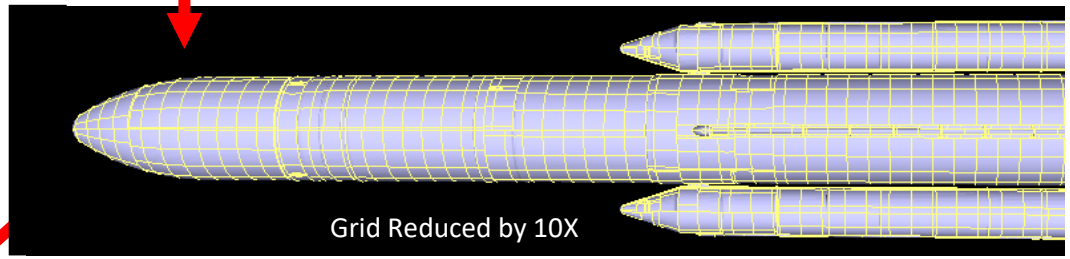
High SNR



Begin Understanding Operational Deployment

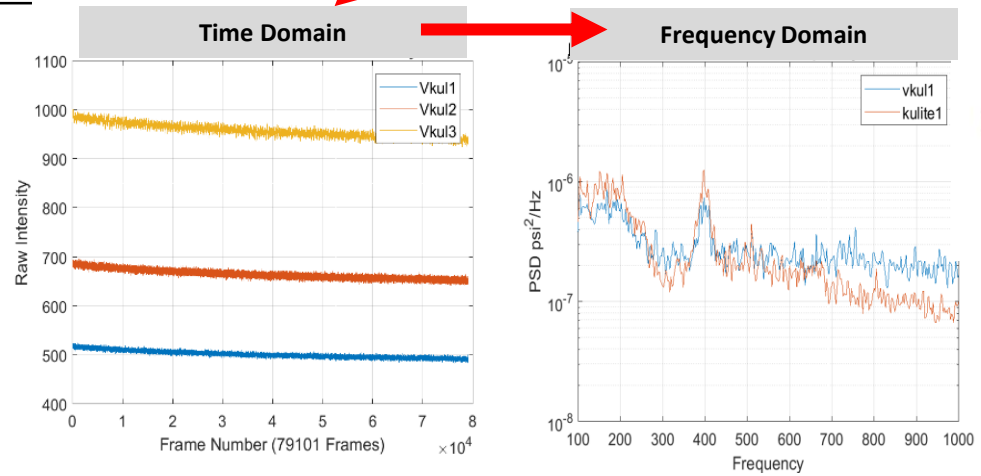


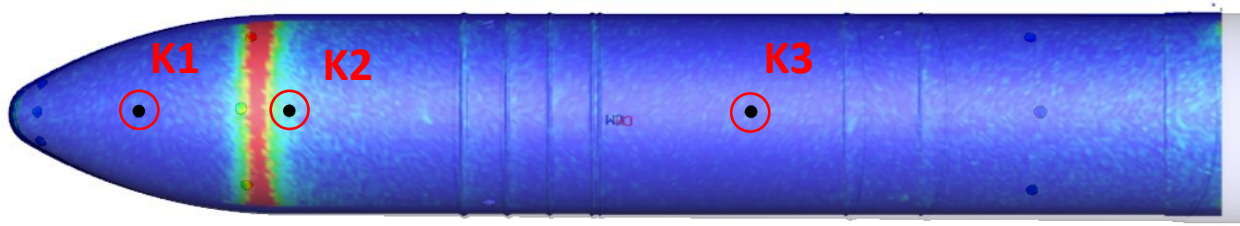
AIAA2018-1031



SLS Force & Moment Test

- Single camera
- 3 Kulites®
- **2 hours of testing**
- **1TB of raw data**

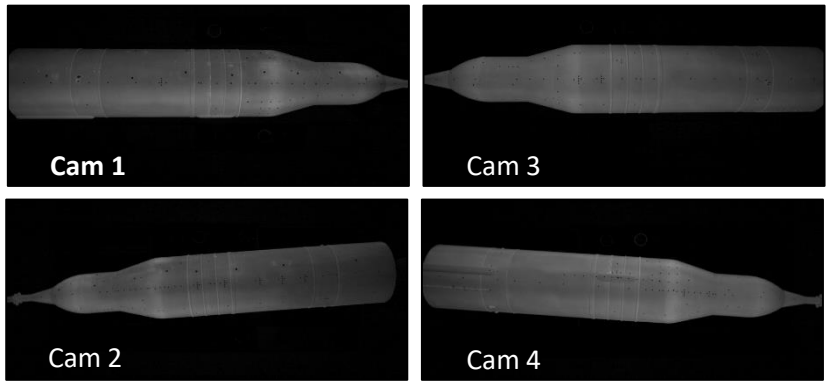


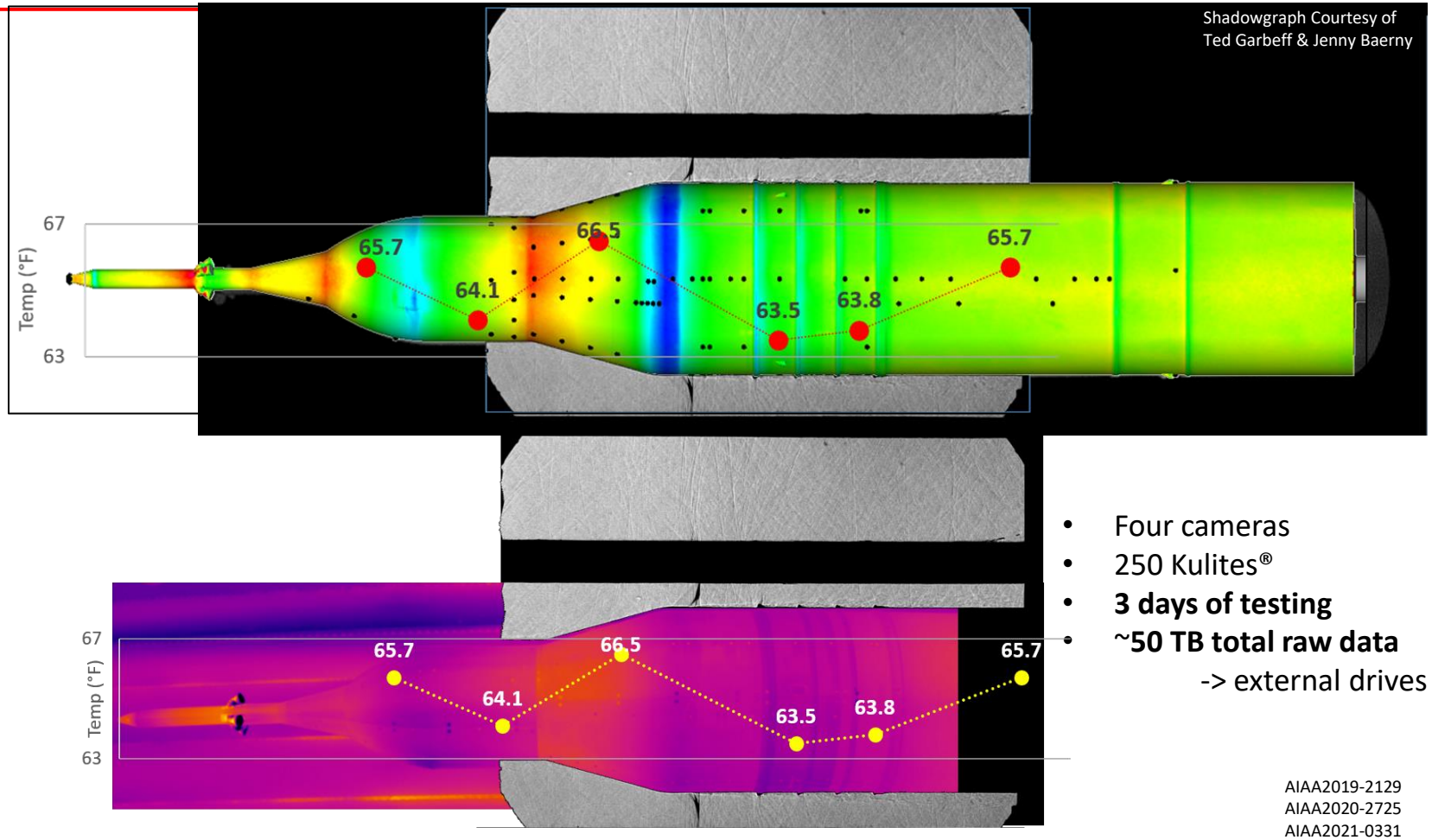


64,000 PSDs at one frequency

- **Needed more storage**
- **Needed better tools to process data**

Begin Understanding Operational Deployment

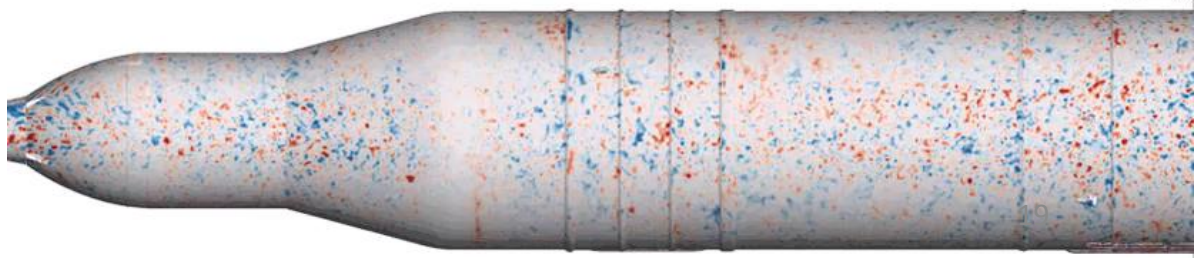




- Four cameras
- 250 Kulites®
- **3 days of testing**
- **~50 TB total raw data**
  -> external drives

AIAA2019-2129
AIAA2020-2725
AIAA2021-0331

- **Performing analysis led to look at other data sources**
- **12 External Hard Drives + 3 months later…**
  Data was processed on NASA Advanced Supercomputer (NAS)



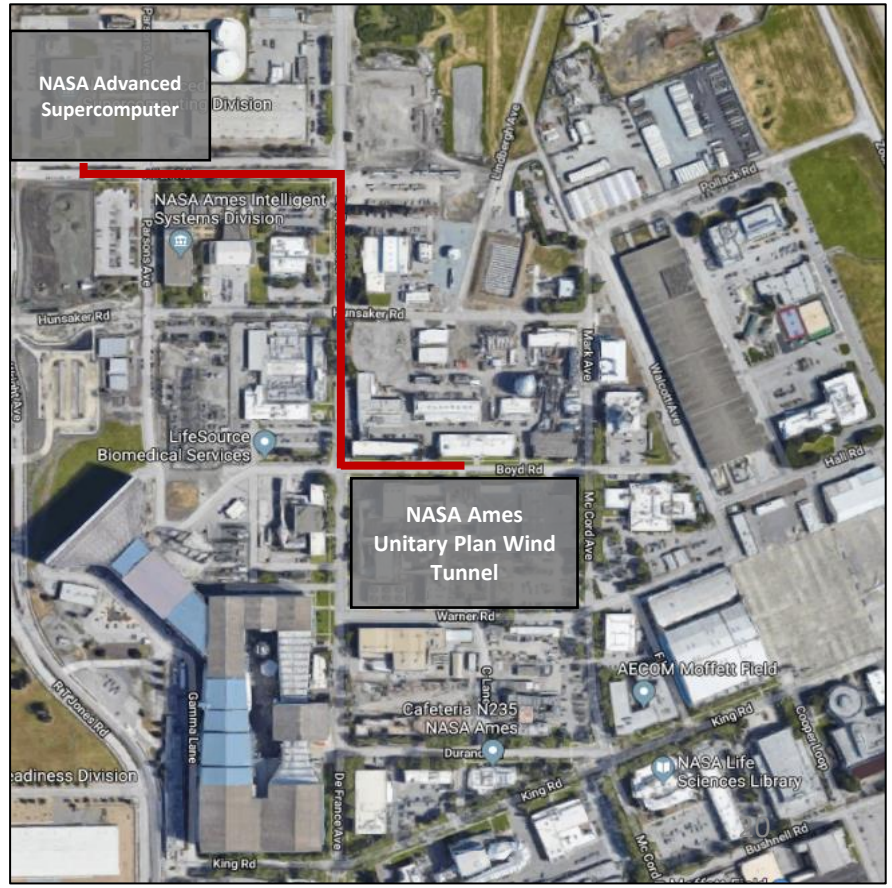
Seasoned Idea but with New Motivation

- Identify the leverage point where efforts would make the biggest difference.
- Connect ***Communities*** and ***Facilities***
- ***Facilitates advancements in model based engineering***

AIAA2020-0516

Red Rover

- Established Connection between UPWT to NAS
- Fast, Powerful, Secure, Reliable
- **Transferred**, **Processed**, and **Visualized** in near real-time
- 150 TB of data in 5 days.



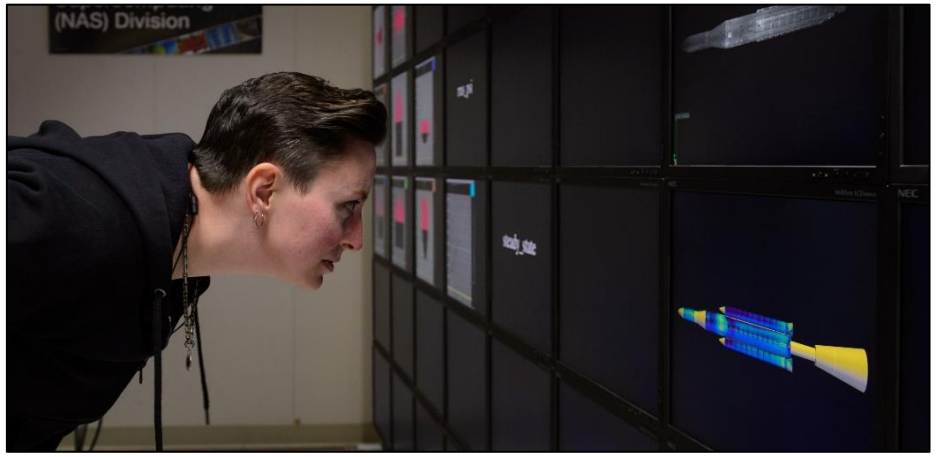
NASA's HECC Goals:

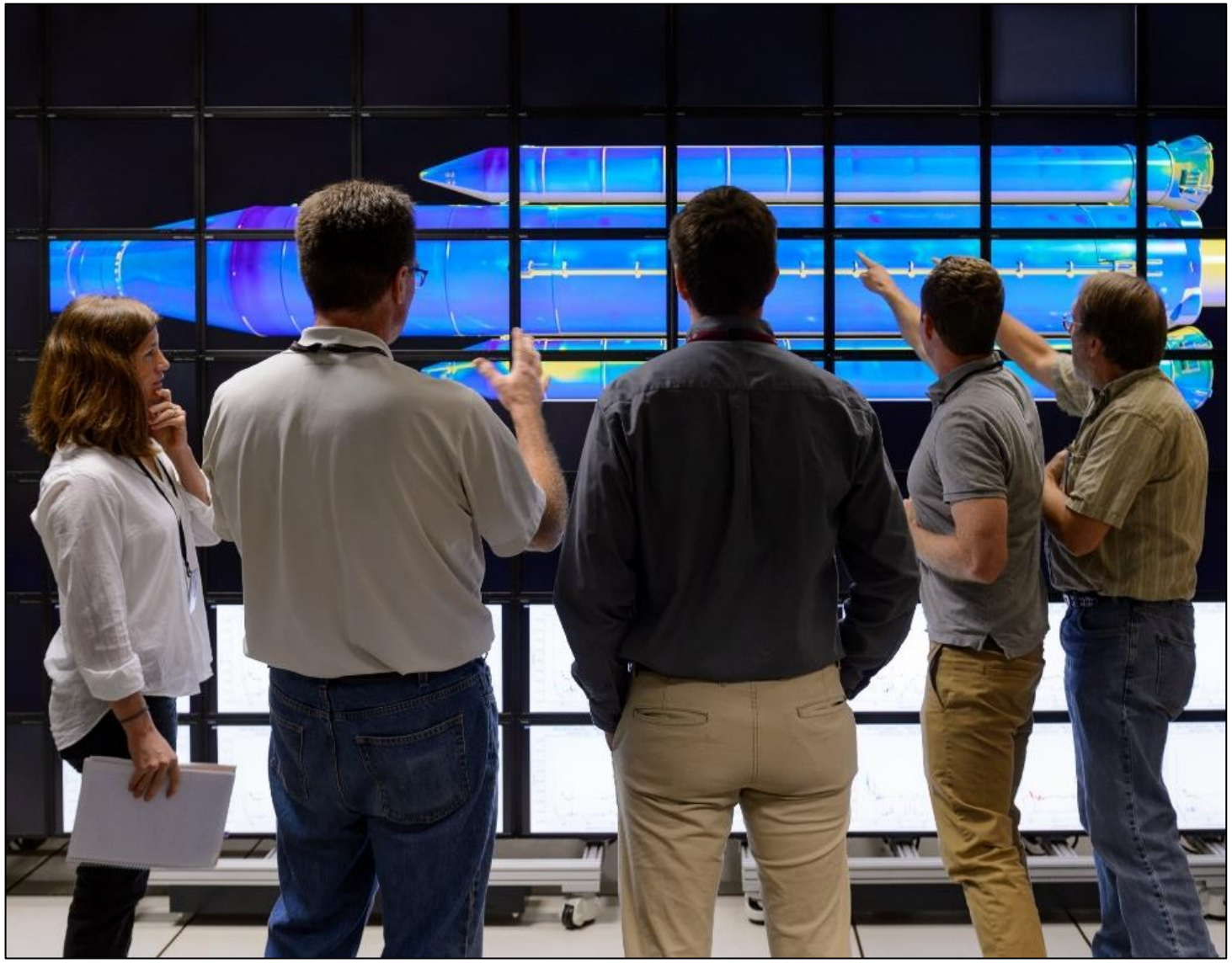
- **Infuse HEC** into NASA's scientific and **engineering communities**.
- Assure preparedness to meet NASA's future modeling, simulation, and **analysis** needs.

Demonstration Creates Conversation

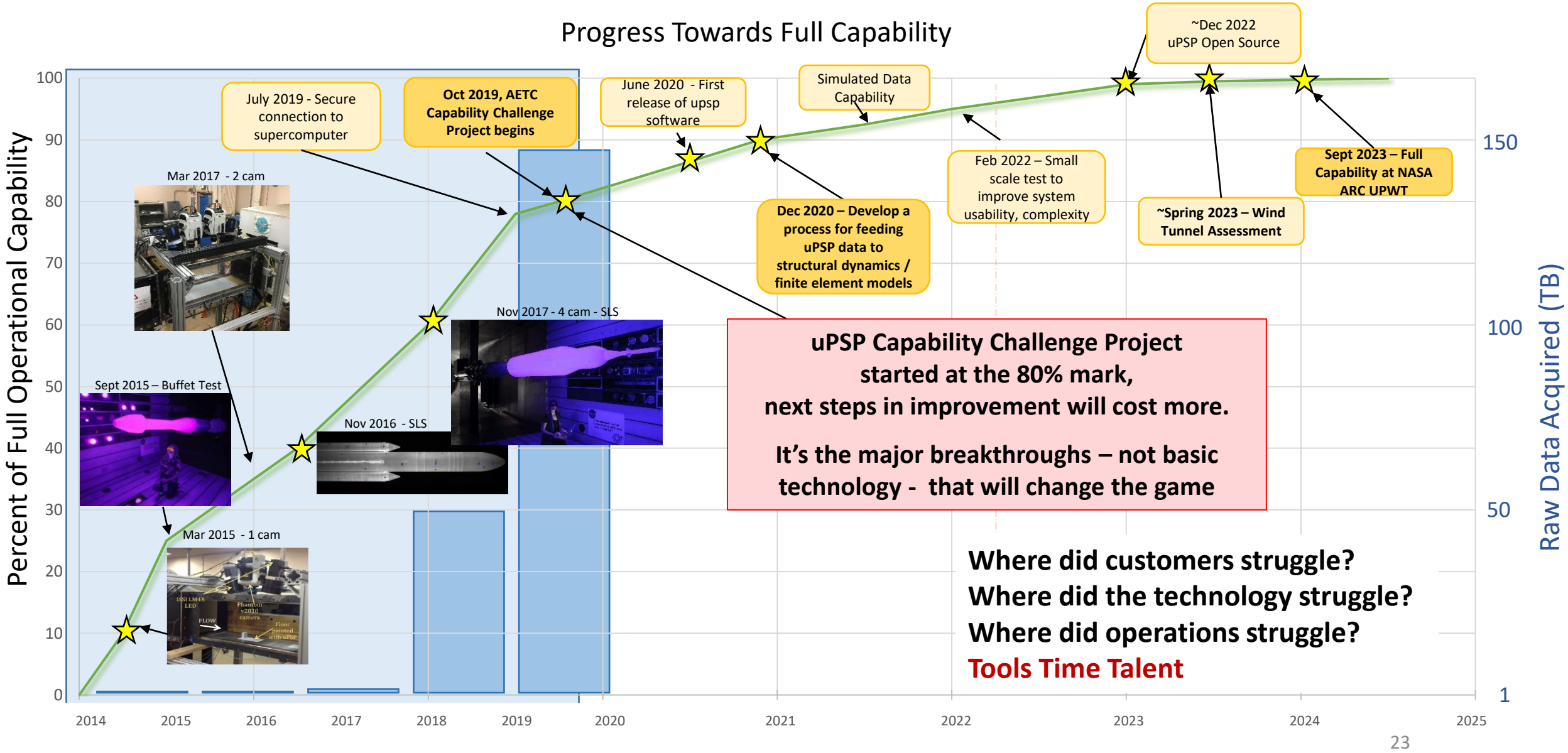
This level of detail had never been measured or seen at this resolution before.

Demonstration Creates Conversation





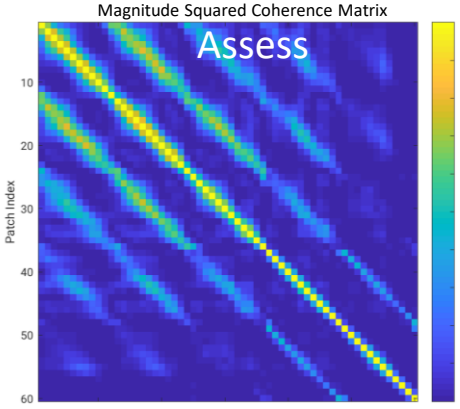
Progress Indicators



Capability Challenge Objective

Develop *a state-of-the-art* ***system*** *to* ***measure, assess, and visualize unsteady aerodynamics*** *for advanced and complex aerospace vehicles at* ***high-resolution*** *and* ***unprecedented data turn-around times****.*

Operational (Data) Pipeline



Research & Development

- Temperature Sensitivities
- Uncertainty Quantification
- Visualization Tools

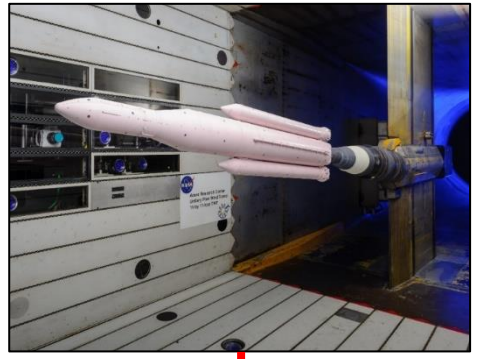
Metrics:

1) Reduce Noise Floor
2) Reduce Time to Process Data
3) Reduce Number of Transducers Required

Current Work

How do we make good decisions?

- **Quality**
  - Uncertainty Quantification Report
    - PSP Sensitivity, Calibration, Photodegradation
    - Camera Noise
    - Data Processing Error
  - Usability of the system
  - Demonstrate uPSP as a tool for tunnel diagnostics
- **Efficiency**
  - Collaborate with structural dynamic, vibroacoustic technical communities
  - Open source uPSP data processing suite
- **Timeliness**
  - Red Rover 2.0
  - Connect users to data



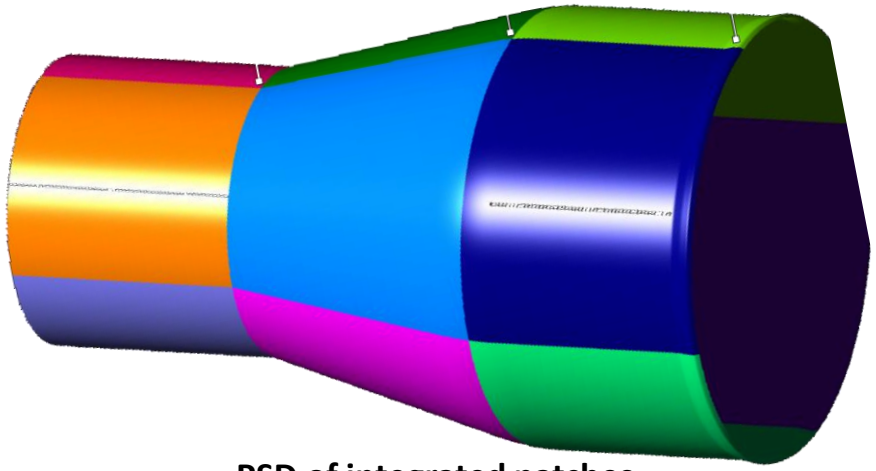
Middle server

Remote user

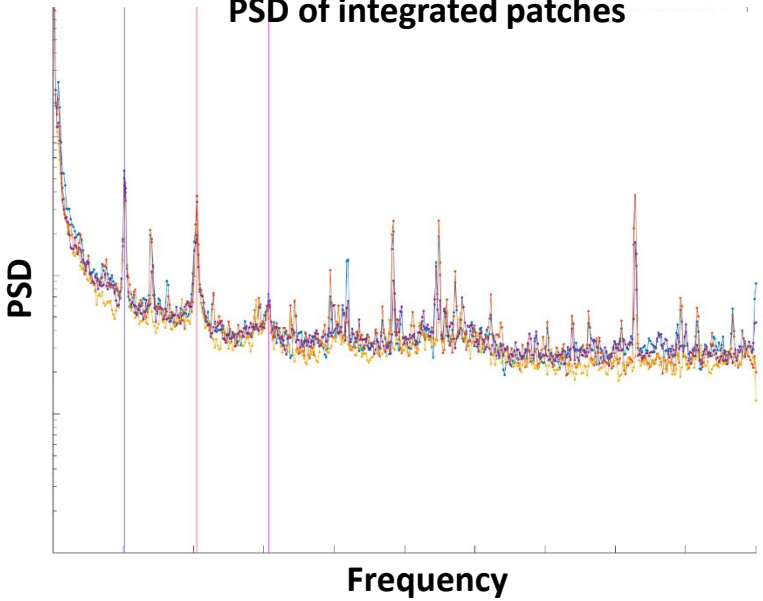
Current Work: Quality & Efficiency

uPSP for tunnel diagnostics / acoustic array

Divided sections of vehicle into large patches

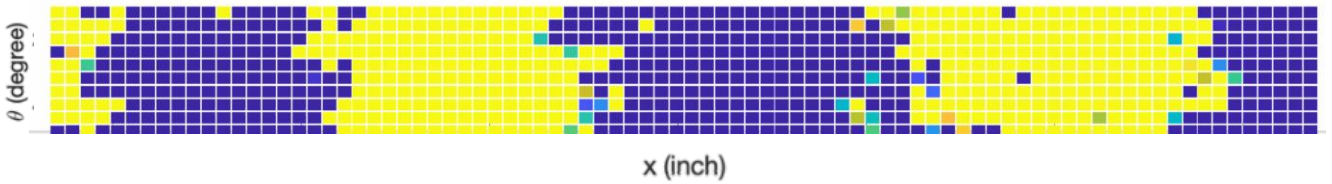


PSD of integrated patches

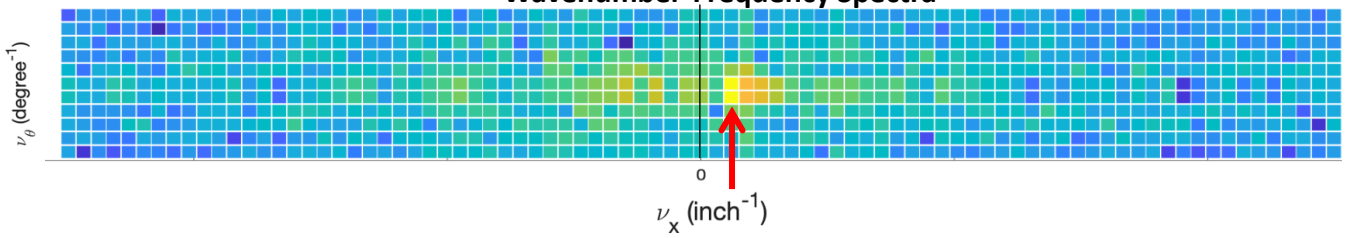


- The uPSP data in each quadrants was integrated.
- Aerodynamic flow features and shot noise is removed by average over large area.
- Remaining spectral peaks are tunnel tones.

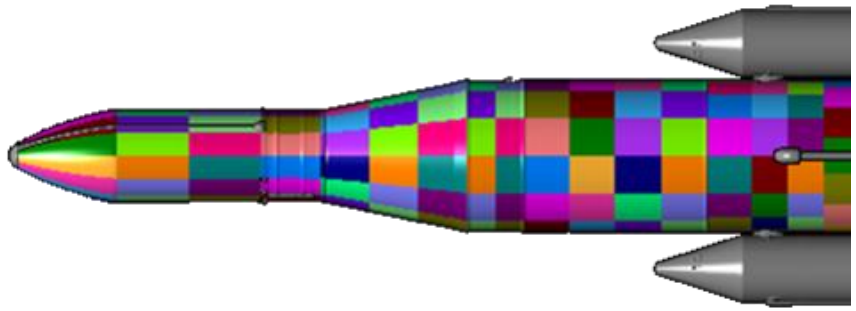
Dynamic Mode Decomposition (DMD)



Wavenumber-Frequency Spectra



Current Work: Efficiency - Establish a Process



From Months to Hours:

- Processed 120 Test Conditions x 300 patches
- Transferred via NAS to SLS NASA/Boeing
- SLS NASA/Boeing ran FEM process (~16 hours)

What's the value:

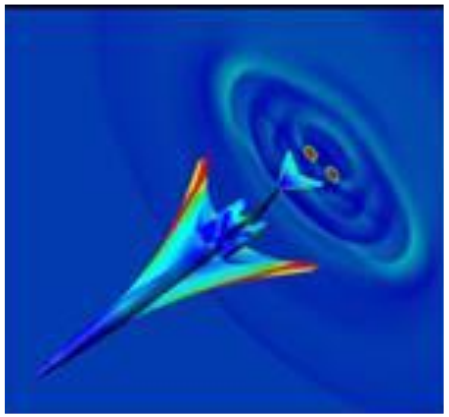
- Benefit was ability to run a wide range of test conditions.
- Data showed:
  - good variation in levels and frequency in high-noise regions.
  - *Area with noise floor concerns.*

Collaboration with SLS program and Boeing has helped the team understand applications and requirements for spacecraft and aircraft wind tunnel models and how the data is used for acoustic analysis.

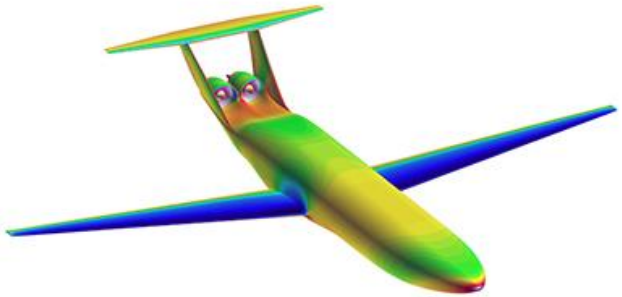
What's the Payoff of the uPSP Capability

NASA Aerosciences

The lack of surface resolution and is on the critical technology list from recent assessment of aerosciences.



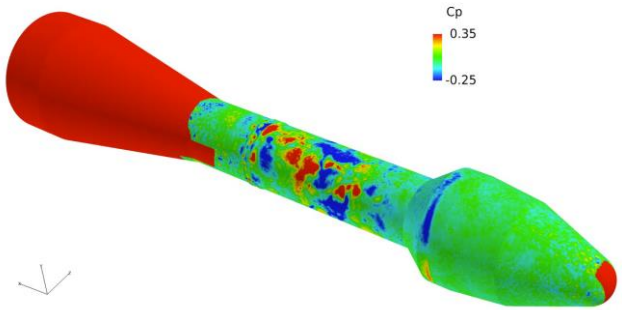
Aviation Sector



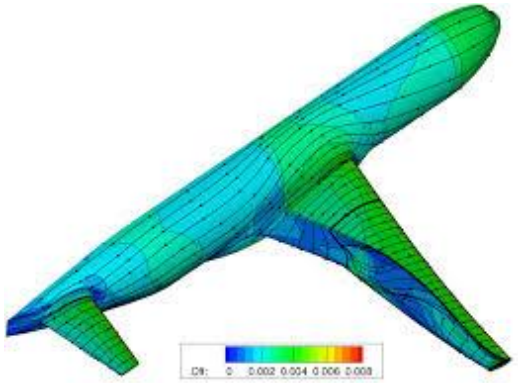
Enable measurement of large areas of unsteady flow providing important insight into the flow physics associated with buffet onset, wake flows, protuberance effects, and fluctuating component loads.

Space Sector

Provide much higher confidence in the measured unsteady loads for measuring launch vehicle buffet.

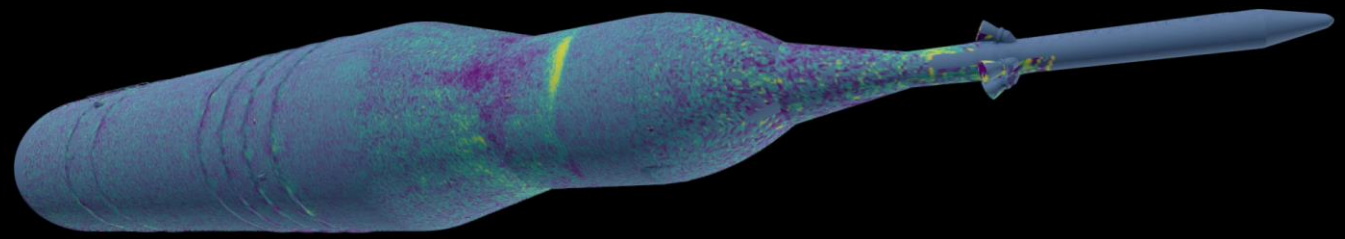


CFD



Provide rich data sets for CFD validation for unsteady flow fields, data that is currently unavailable except in small glimpses using traditional sensors.

Unsteady PSP has the ability to transform unsteady flow assessment.



The culture, people, processes, technology, and facilities that allowed NASA to CONTINUE successfully lead the space programs.

Summary

- Measurement of Unsteady Surface Pressures is **critical** to design aerospace vehicle
  - Improving the state of the art, will reduce margins
  - Develop uPSP technology - from research lab to a production wind tunnel **capability**
- **Must** connect *Experimental* and *Computation* Facilities and Communities
  - People + Facilities + Tools
  - Facilitate advancements in model-based engineering, data-driven modeling
  - 'Get the data in the right environment'
- AETC uPSP Capability Challenge Project - Demonstration Creates Conversation
  - Advance the state of the art in …
  - Real-time steering of wind tunnel experiment